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A new approach for exhaust energy recovery of internal combustion engine: Steam turbocharging

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HIGHLIGHTS

► A new concept of steam turbocharging is proposed to boost IC engine intake pressure.
► In exhaust turbocharging system, nearly half of turbine output work comes from the piston work.
► The performances of steam turbocharging system can be optimized by adjusting steam pressure and flow rate.
► The power of steam turbocharging engine can be improved by 7.2% at most on the basis of exhaust turbocharging engine.
► IC engine thermal efficiencies can be improved by 2 percent points or more except at 1000 r/min.

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ABSTRACT

In this paper, a new concept of steam turbocharging was proposed to boost IC engine intake pressure. A set of Rankine steam cycle system is coupled on IC engine exhaust pipe, which uses IC engine exhaust energy to generate steam and then drive the turbine. Part of steam expansion power is used to drive air compressor, and the remainder is recovered by motor. To compare with exhaust turbocharging, the two kinds of boosting pressure methods are applied on the same IC engine, and the working processes of steam turbocharged engine and exhaust turbocharged engine were simulated. On this basis, the differences between two kinds of boosting pressure methods were analyzed, and IC engine performance enhancement potentials by using steam turbocharging system were obtained. The results show that IC engine power can be theoretically improved by 7.2% at most, and thermal efficiencies can be improved by 2 percent points or more except at 1000 r/min by using steam turbocharging. All these can prove this boosting pressure concept is a novel technology with great energy saving potentials.

1. Introduction

A lot of research indicates that boosting intake pressure is a useful way to improve both the power performance and fuel economy of internal combustion engine (IC engine). From the viewpoint of IC engine energy balance [1–3], higher intake pressure results in higher brake mean effective pressure (BMEP), and finally it leads to higher thermal efficiency and power. At the same time, boosting intake pressure can also achieve the goal of downsizing IC engine displacement, thus most of modern advanced IC engines adopt various technologies of boosting pressure. In these boosting pressure technologies on IC engine, such as supercharger, electricity aided turbo (EAT), exhaust turbocharging is used most widely. Actually, exhaust turbocharging is also a kind of method for IC engine exhaust energy recovery (EER), since it uses IC engine exhaust pressure energy to drive the turbine [4].

However, IC engine exhaust turbocharging is not so good for exhaust energy recovery. J.P. Liu et al. [5] have investigated the energy flow of a diesel engine turbocharged system and concluded that the energy recovery efficiency of exhaust turbocharging system is largely determined by the turbocharger efficiency and only a small part of exhaust energy can be recovered. This is because the major form of exhaust energy is thermal energy rather than pressure energy [6]. At the same time, exhaust turbocharging inevitably brings additional exhaust back pressure to IC engine, and it results in the consequence that IC engine has to consume more effective work during the exhaust process. As a result, most of the exhaust energy recovered by turbocharger is used to overcome the additional pumping loss. Sometimes, if the exhaust turbine does not match the compressor well, the recovered exhaust energy will

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even be less than the additional pumping loss. Moreover, the boosting pressure often cannot reach the desired value under IC engine low-speed. Consequently, exhaust turbocharging is neither the best way to recover exhaust energy nor the best way to boost intake pressure for IC engine. In this paper, we propose a novel concept which uses IC engine exhaust thermal energy to boost intake pressure. As this concept is based on the principle of steam power cycle, it is named as steam turbocharging, which is different from IC engine exhaust turbocharging. Meanwhile, both the steam turbocharging and exhaust turbocharging are applied on the same IC engine, and the performances of IC engine with the two kinds of turbocharging means are compared, for the purpose of demonstrating the advantages and feasibility of steam turbocharging.

2. IC engine exhaust energy characteristics

Limited by the expansion ratio of IC engine cylinder, fuel gas cannot fully expand in cylinder. As a result, part of fuel energy is taken away by exhaust and wasted in the environment. Fig. 1 shows the energy distributions of an exhaust turbocharged diesel engine. It illustrates that diesel engine exhaust energy is nearly the same as effective work in the whole speed range under full load. Because the pressure and temperature of IC engine exhaust are higher than those of ambient, correspondingly, IC engine exhaust contains the pressure energy and thermal energy [6]. In the exhaust energy, pressure energy belongs to mechanical energy and can be directly recovered or reused by exhaust expanding. However, the energy grade of exhaust thermal energy is determined by exhaust temperature. As shown in Fig. 2, in the whole speed range under full load, the exhaust temperature of turbocharged diesel engine is between 844 K and 953 K. Accordingly, the energy grade of exhaust thermal energy changes from 0.65 to 0.69. Compared to the IC engine effective work (whose energy grade is 1), the exhaust thermal energy is a kind of low-grade energy. At the same time, the recovery process of exhaust thermal energy depends on some indirect methods, such as heat transfer and thermodynamic cycle, thus the recovery process is more complex than the direct recovery means. Moreover, the main form of exhaust energy is thermal energy since it takes the largest proportion all along [6]. According to the characteristics of two forms of exhaust energy, there come two kinds of methods for IC engine exhaust energy recovery, which are direct recovery method based on exhaust direct expanding and indirect recovery method based on heat transfer and thermodynamic cycle [7]. Recently, how to reuse the exhaust energy to improve IC engine performances especially its total fuel efficiency becomes a research hotspot in the IC engine field [8–12]. For example, J.C. Conklin and J.P. Szybist have proposed a six-stroke IC engine cycle with water injection for in-cylinder exhaust heat recovery, and they claimed that this concept has the potential to significantly increase the IC engine efficiency and fuel economy [13]; T.Y. Wang et al. have analyzed the recoverable exhaust energy from a light-duty gasoline engine by combining the experimental and modeling research. And the results demonstrate the EER system based on light-duty test engine could increase the engine fuel conversion efficiency up to 14%, though under general vehicle operating conditions it was just between 3% and 8% [14]. Being different from these existing methods for exhaust energy recovery, in this paper, the exhaust energy is used to boost IC engine intake pressure through steam power cycle, and the performance improvement of IC engine is discussed in the next.

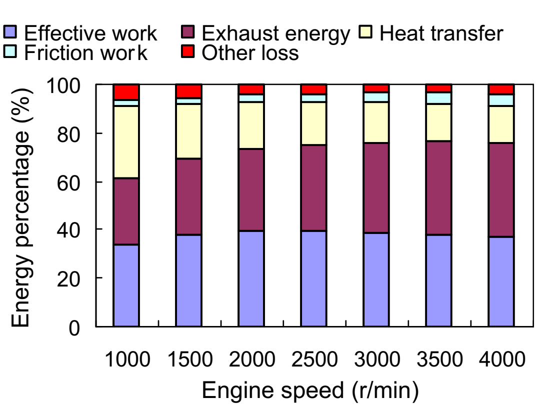

Fig. 1. Energy distributions of a turbocharged diesel engine.

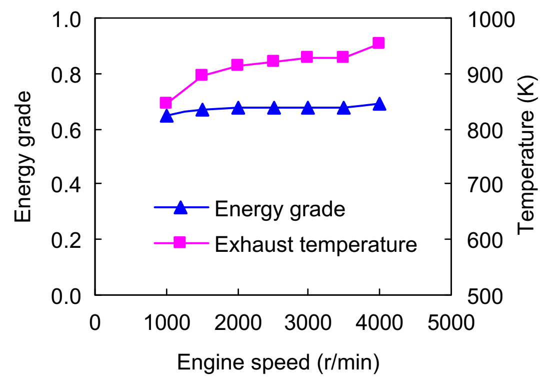

Fig. 2. Exhaust temperature and energy grade of turbocharged diesel engine.

3. IC engine exhaust turbocharging

3.1. Technical problems of exhaust turbocharging

It is well known that exhaust turbocharging is the first concept to reuse IC engine exhaust energy [15]. In exhaust turbocharging system, IC engine exhaust expands again in turbine and outputs shaft work to drive air compressor. By this means, exhaust energy is used to boost IC engine intake pressure. According to the previous analysis, exhaust turbocharging is a kind of direct method for exhaust energy recovery. Lots of research shows that it is a successful approach to improving IC engine performances. At present, almost all the boosting pressure engines are equipped with exhaust turbocharger except that only a small part of engines, e.g. submarine engine, use supercharger.

In exhaust turbocharging system, turbine is directly coupled on the IC engine exhaust pipe so as to use the exhaust as working medium. Although there is no mechanical connection between the turbine and IC engine, they have a closed connection through the exhaust. As IC engine exhaust parameters change wildly, turbine working performances are impacted by the exhaust. Then, turbine working performances determine compressor working performances through the transmission shaft. Finally, compressor working performances affect IC engine performances by influencing the intake pressure. In a word, the performances of turbine, compressor and IC engine influence each other. Therefore, the matching processes among turbine, compressor and IC engine become a very difficult technology since IC engine working conditions often change. Furthermore, the main faults of exhaust turbocharging can be summarized as follows: 1) Due to the exhaust throttling in turbine, there is a higher exhaust back pressure and larger exhaust loss in exhaust turbocharged engine; 2) It is hard to match exhaust turbocharger and IC engine because of the pulsation of exhaust parameters; 3) At low-speed, pressurization degree is

not high enough since the exhaust pressure is very low; at high-speed, the mass flow rate of exhaust is so high that part of exhaust should be bypassed. As a result, part of exhaust energy is wasted; 4) From the viewpoint of exhaust energy recovery, turbocharger only recovers a small part of exhaust energy and the recovery efficiency is very low. Consequently, most of exhaust energy is still wasted [5].

3.2. Analysis on the pumping loss of exhaust turbocharged engine

As mentioned previously, one of the biggest defects of exhaust turbocharging is that IC engine with exhaust turbocharging system has higher pumping loss, which directly affects the power performance and fuel economy of IC engine. For this reason, how to reduce or even completely remove the additional pumping loss becomes a key issue of exhaust turbocharging. In order to better analyze the relationship between pumping loss and IC engine performance, the following equation is given

$$\mathrm{BMEP} = \mathrm{IMEP} + \mathrm{PMEP} - \mathrm{FMEP} \tag{1}$$

where, BMEP is the brake mean effective pressure, which is one of the most important parameters of IC engine power performance; IMEP is the indicated mean effective pressure; PMEP is the pumping mean effective pressure; FMEP is the friction mean effective pressure.

Generally, IMEP is determined by the mass flow rate of intake and fuel, and FMEP depends on the mechanical friction loss of IC engine. However, PMEP is subject to the gas exchange process, and it is directly influenced by intake pressure and exhaust pressure. Combining with the schematic diagram for IC engine exhaust turbocharging system shown in Fig. 3, the relationship among intake pressure, exhaust pressure and PMEP is given as

$$\mathrm{PMEP} = p_2 - p_3 - p_{\mathrm{cyl\_port\,loss}} \tag{2}$$

where, p_3 is the mean exhaust pressure of IC engine; p_2 is the mean boosting pressure (compressor outlet pressure); $p_{\mathrm{cyl\_port\,loss}}$ is the mean pressure loss in the intake ports and cylinder. Through analyzing on Equation (2), the following conclusions can be drawn. If IC engine intake pressure is higher than exhaust back pressure, PMEP will be positive. Under the circumstances, gas exchange processes do positive work to the IC engine. Conversely, PMEP will be negative, and IC engine has to consume some effective work in the gas exchange processes.

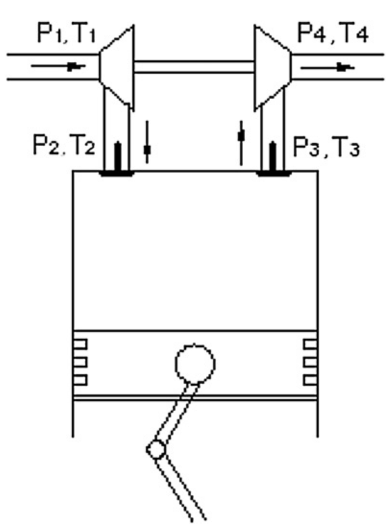

Fig. 3. Schematic diagram for exhaust turbocharging system.

Fig. 4 gives the *P–V* diagram of in-cylinder cycle for exhaust turbocharged engine. As it can be observed, the pumping loss consumes a part of cycle work. During the intake process, because intake pressure of turbocharged engine is higher than ambient pressure, intake process does positive work to the piston. However, during the exhaust process, because exhaust pressure is greater than ambient pressure, exhaust process does negative work to the piston. As is well-known, the pumping loss of exhaust turbocharged engine equals intake process work minus exhaust process work. In the exhaust process, exhaust back pressure directly acts on the IC engine piston. Therefore, any means for exhaust energy recovery at the expense of improving IC engine exhaust back pressure, if the output work of turbine is lower than the additional pumping work due to additional exhaust back pressure, the loss will outweight the gain. Because the exhaust turbocharging is directly related to exhaust pressure, and exhaust pressure directly affects the IC engine pumping loss, there are many constraints for exhaust turbocharging. What's more, the effective working area of exhaust turbocharging system, which is subject to the turbocharger efficiency, is very limited.

4. IC engine steam turbocharging

4.1. Principles of steam turbocharging system

In order to solve the problems of exhaust turbocharging, the new approach of steam turbocharging is proposed, which is based on the principle of Rankine steam cycle [16,17]. According to the previous analysis, steam turbocharging is a kind of indirect method for exhaust energy recovery. That is, it recovers IC engine exhaust thermal energy by the means of heat transfer, and makes the recovered exhaust energy convert into the effective output work of turbine. Finally, the turbine output work is used to drive air compressor. The schematic diagram of steam turbocharging system is given in Fig. 5 below.

As shown in Fig. 5, the steam turbocharging system consists of water tank, valve, pump, heat exchanger, steam turbine, motor and air compressor, etc. In these components, valve is used to adjust the flow rate of working medium water, while pump is used to control the cycle pressure. A motor is coupled on the transmission shaft for the purpose of managing bottom cycle energy flow. The operating modes of motor are described as follows. (1) Driving the air compressor: when IC engine starts, the steam turbine does not work immediately and air compressor is driven by the motor to obtain an expected compression pressure; when IC engine works at

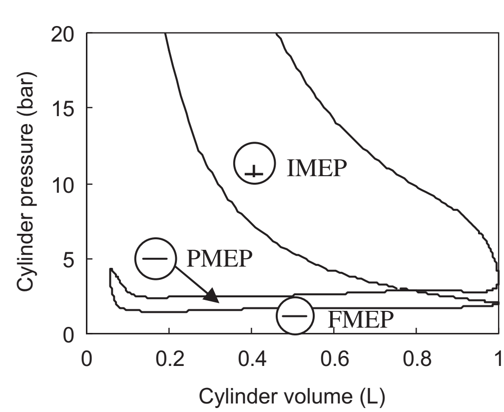

Fig. 4. *P–V* diagram of in-cylinder cycle for exhaust turbocharging engine.

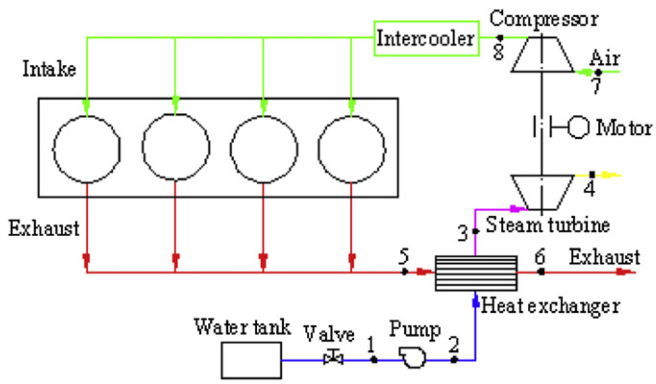

Fig. 5. Schematic diagram of steam turbocharging system.

low-speed and low-load operating conditions, air compressor is driven by both the steam turbine and motor, since exhaust energy is very low. (2) Generating electric energy: when IC engine works at high-load operating conditions, steam turbine output power may be larger than the power required by air compressor. In this situation, both the air compressor and motor are driven by the steam turbine. As a result, extra output power of steam turbine can be stored in the form of electric energy by motor.

The steam turbocharging system shown in Fig. 5 is a kind of open steam power cycle. Actually, it can be designed into both open steam power cycle [18] and closed steam power cycle [14]. Correspondingly, the two kinds of bottom cycle have different applications. Usually, the open steam power cycle is much simpler than the closed steam power cycle, since there is no condenser and condensation process in the former. And the system costs of the former are also much lower than the latter. The steam turbocharging system based on open steam power cycle is suitable for stationary applications, e.g. genset, steam plant. Under the circumstances, this should not be an issue for the working medium water. However, the steam turbocharging system based on closed steam power cycle has more widely applications since the working medium water can be recycled. Generally, it can be used in both the stationary applications and the mobile power sources, such as automobile engine and marine engine. The working principles of open steam power cycle and closed steam power cycle are almost the same. In this paper, we have only analyzed the open steam power cycle.

In the steam turbocharging system, water is used as bottom cycle working medium, and the *T–S* diagram corresponds to the thermodynamic processes of working medium water is shown in Fig. 6. Combining Figs. 5 and 6, the thermodynamic processes of steam turbocharging bottom cycle are described as follows. Process 1–2: in the pump, liquid working medium water is compressed to

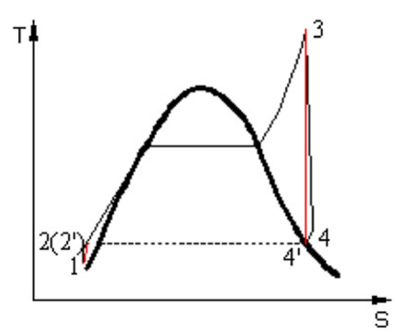

Fig. 6. *T–S* diagram of Rankine steam cycle system.

a certain pressure, and this process corresponds to process 1–2(2′) in the *T–S* diagram. Process 1–2′ represents the ideal process (isentropic compression) while process 1–2 is the real compression process. Process 2–3: in the heat exchanger, liquid working medium water is heated into superheated steam by IC engine exhaust, and this process can be regarded as an isobaric process with the pressure loss ignored. Process 3–4: in the turbine, superheated steam expands and outputs effective work. In the *T–S* diagram, process 3–4′ represents the ideal expansion process (isentropic expansion), and process 3–4 is the real expansion process (irreversible expansion).

4.2. Analysis on the characteristics of steam turbocharging system

Compared to exhaust turbocharging, steam turbocharging has lots of advantages, which can be summarized as follows. 1) By coupling the motor on transmission shaft, steam turbocharging system has better transient response performance and higher exhaust energy recovery efficiency. Furthermore, IC engine has an expected boosting pressure even at low-speed and start working conditions. 2) In exhaust turbocharging system, turbine can only passively accept the IC engine exhaust. Because exhaust parameters fluctuate with IC engine working conditions, exhaust turbocharging system cannot often work in the optimal range. And yet, things change in the steam turbocharging system. The parameters of steam turbocharging system, such as steam flow rate, pressure, can be adjusted and optimized. As a result, steam turbocharging system can often work in the optimal range. 3) Thirdly, IC engine working cycle relates steam turbocharging bottom cycle through heat transfer rather than pressure transmission. By this means, steam turbocharging decouples IC engine exhaust pressure and bottom cycle working pressure through heat transfer, and the exhaust pressure of steam turbocharging engine can be largely reduced on the basis of exhaust turbocharging engine. Consequently, the exhaust process work of steam turbocharging engine can also be reduced, and the pumping work of steam turbocharging engine in gas exchange process may change from negative to positive.

4.3. Calculation formulas for steam turbocharging system

Combining with the *T–S* diagram of Rankine steam cycle shown in Fig. 6, the performance parameters and calculation formulas for steam turbocharging system are defined. Firstly, calculation formula for the compression power consumed by pump is given as

$$P_{\mathrm{pum}} = \dot{m}_{\mathrm{st}} \cdot (h_{2'} - h_1) \cdot \frac{1}{\eta_{\mathrm{pum}}} \tag{3}$$

where, P_{pum} is the compression power of pump; $\dot{m}_{\mathrm{st}}$ is the mass flow rate of working medium; η_{pum} is the isentropic efficiency of pump; h_1 and $h_{2'}$ are the specific enthalpy of working medium at the corresponding state points in the *T–S* diagram of Fig. 6.

In the steam turbine, steam expands and then outputs effective work. The calculation formula for steam expansion power is given as

$$P_{\mathrm{tur}} = \dot{m}_{\mathrm{st}} \cdot (h_3 - h_{4'}) \cdot \eta_{\mathrm{tur}} \tag{4}$$

where, P_{tur} is the output power of steam turbine; η_{tur} is the isentropic efficiency of steam turbine; h_3 and h'_4 are the specific enthalpy of steam at state point 3 and state point 4′, respectively.

In the heat exchanger, liquid working medium water is heated into superheated steam by IC engine exhaust. During this process, working medium state changes from state point 2 to state point 3. At the same time, IC engine exhaust is cooled from state point 5 to

state point 6. According to the energy conservation law, the following formulas are given

$$\dot{\Phi}_{5-6} = \dot{m}_{\mathrm{ex}} \cdot (h_5 - h_6) = \dot{\Phi}_{2-3} \tag{5}$$

$$\dot{\Phi}_{2-3} = \dot{m}_{\mathrm{st}} \cdot (h_3 - h_2) \tag{6}$$

where, $\dot{\Phi}_{2-3}$ is the heat flux flows into steam; $\dot{\Phi}_{5-6}$ is the heat flux flows out of IC engine exhaust; h_5 and h_6 are the specific enthalpy of IC engine exhaust at state point 5 and state point 6, respectively, as shown in the schematic diagram of steam turbocharging system in Fig. 5; h_2 is the specific enthalpy of working medium at state point 2.

In this steam turbocharging bottom cycle, the output power equals turbine expansion power minus pump power, and its calculation formula is written as

$$P_{\mathrm{out}} = P_{\mathrm{tur}} - P_{\mathrm{pum}} \tag{7}$$

where, P_{out} is the output power of steam turbocharging bottom cycle.

As mentioned earlier, a part of bottom cycle output power is used to drive the air compressor, and the extra power is recovered by the motor. The power balance among bottom cycle output power, compressor power and motor power is given as

$$P_{\mathrm{mot}} = P_{\mathrm{out}} - P_{\mathrm{com}} \tag{8}$$

where, P_{mot} is the extra power recovered by motor, which is also the net output power of steam turbocharging bottom cycle; P_{com} is the power required by air compressor, whose calculation formula is given as

$$P_{\mathrm{com}} = \dot{m}_{\mathrm{in}} \cdot c_P \cdot (T_8 - T_7) = \dot{m}_{\mathrm{in}} \cdot c_P \cdot T_7 \left[\left(\frac{p_8}{p_7} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \cdot \frac{1}{\eta_{\mathrm{com}}} \tag{9}$$

where, $\dot{m}_{\mathrm{in}}$ is the mass flow rate of intake gas; c_P is the constant-pressure specific heat of intake gas; T_7 and T_8 are the intake gas temperature at the inlet and outlet of compressor, respectively; p_7 and p_8 are the intake gas pressure at the inlet and outlet of compressor, respectively; γ is the specific heat ratio of intake gas; η_{com} is the isentropic efficiency of compressor.

Next, the calculation formulas for IC engine performance parameters are also given. The effective power of IC engine can be calculated as

$$P_e = \frac{p_{\mathrm{me}} \cdot V_s \cdot n \cdot i}{30\tau} \tag{10}$$

where, P_e is the effective power of IC engine; p_{me} is the brake mean effective pressure of IC engine; V_s is the displacement of each cylinder; n is the IC engine speed; i is the number of cylinder; τ is the number of stroke.

The calculation formula for IC engine effective thermal efficiency is given as

$$\eta_t = \frac{3.6 \times 10^3 P_e}{B \cdot H_u} \tag{11}$$

where, η_t is the effective thermal efficiency of IC engine; B is the consumption of fuel in per hour; H_u is the low heat value of fuel.

Finally, as a vital parameter for IC engine fuel economy, the brake specific fuel consumption (BSFC) of IC engine can be calculated as

$$b_e = \frac{B}{P_e} \times 10^3 \tag{12}$$

where, b_e is the BSFC of IC engine.

5. Calculation for two kinds of boosting pressure models

In order to compare the performances of steam turbocharging and exhaust turbocharging, both the two kinds of boosting pressure models are applied on the same IC engine. A four stroke, direct injection, water-cooled, four cylinder, exhaust turbocharged diesel engine is used for this investigation. The displacement of this diesel engine is 1.57 L, and the turbocharged system is equipped with the technology of variable geometry turbocharger (VGT). Details of the diesel engine specifications are listed in Table 1. According to the geometry structural parameters and performance experimental data of this diesel engine, the corresponding numerical simulation model was established by using the IC engine simulation software of GT-power. The simulation model of target diesel engine consists of intake module, body module (cylinder and crankcase), exhaust module and boosting pressure module, etc., as shown in Fig. 7. In this model, boundary conditions of inlet and outlet, e.g. ambient temperature and pressure, were set to the parameters of standard atmospheric state. Other parameters, such as mechanical friction loss, combustion efficiency, air/fuel ratio, flow coefficient of intake valve and exhaust valve, were calibrated by experimental data of this diesel engine.

Next, part of calculation results of exhaust turbocharging engine, such as the power and torque, are compared to the bench test data, as shown in Fig. 8 and Fig. 9, respectively. As can be seen from the two figures, the calculation data are well consistent with the experimental data, and the maximum error is within 5%. All those demonstrate that the GT-power simulation model has enough precision and reliability, and it meets the requirement for simulation calculation. Then, the simulation model of steam turbocharging engine was established on the basis of the simulation model of exhaust turbocharging engine by removing the turbocharger and resetting the inlet pressure. As a result, the two models have the same boosting pressure.

6. Calculation results and analysis

6.1. Analysis on the steam turbocharging bottom cycle

Firstly, the performances of steam turbocharging bottom cycle are discussed. The initial parameters and boundary conditions of steam turbocharging bottom cycle are listed in Table 2. Speeds of 1000 r/min, 2000 r/min, 3000 r/min and 4000 r/min are investigated under IC engine full load. Based on the calculation formulas given above, the output power of steam turbocharging bottom cycle is acquired under various kinds of steam pressure and mass flow rate, and the results are shown in Fig. 10(a)–(d). As can be

Table 1
The basic parameters of diesel engine.

Item	Content
Engine type	Inline four cylinder
Bore (mm)	75
Stroke (mm)	89
Displacement (L)	1.573
Compression ratio	18
Ignition mode	1-3-4-2
Max torque [N m/(rpm)]	230/2000
Rated power [kW/(rpm)]	80/4000

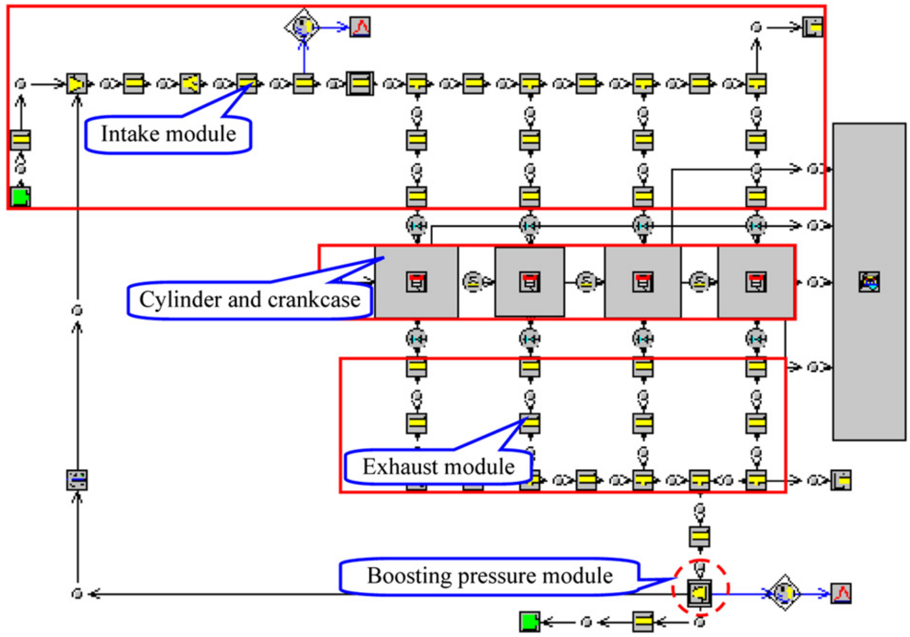

Fig. 7. Numerical model of the IC engine in GT-power.

observed from these figures, at the fixed IC engine speed, bottom cycle output power is influenced by both the steam pressure and mass flow rate. On one hand, higher steam pressure corresponds to higher output power. On the other hand, as the steam pressure is fixed, less steam flow rate also results in higher output power. However, compared to the steam mass flow rate, steam pressure plays a more important role in the bottom cycle output power. Moreover, different speed corresponds to different bottom cycle output power as well as steam flow rate range since exhaust parameters change with IC engine speed. Actually, when IC engine exhaust parameters are fixed, steam flow rate and pressure determine the outlet steam temperature of heat exchanger (point 3), while the outlet steam temperature of heat exchanger is limited by two constraint conditions. That is, the highest outlet steam temperature should be lower than the IC engine exhaust temperature, and the lowest outlet steam temperature should be higher than the corresponding saturated steam temperature. As a result, different exhaust parameters determine different steam flow rate range as well as the bottom cycle output power. With the increasing of IC engine speed, both the bottom cycle output power and steam flow rate range are improved, as shown in Fig. 10.

Through analyzing these figures, the following consequences can be summarized. On one hand, with the rising of IC engine speed, both the exhaust temperature and mass flow rate increase, and it leads to the increasing of exhaust energy. As a result, higher IC engine speed corresponds to more bottom cycle output power. On the other hand, at the fixed IC engine speed, as the steam pressure rises, the power consumed by pump increases a little, while the specific enthalpy of steam increases a lot. Consequently, steam expansion work can be improved significantly. Fig. 11 gives the required compressor power and pressure ratio of this diesel engine under full load, both of which increase with the IC engine speed. In order to better evaluate the power balance relationship of steam turbocharging system, compressor power is also plotted in Fig. 10. At the speed of 1000 r/min, compressor power is only 0.7 kW, so the required minimum steam pressure should be around 0.4 MPa to keep the power balance between steam turbine and air compressor. When the steam pressure is higher than 0.4 MPa, bottom cycle output power can be larger than compressor power. Under the circumstances, the extra output power is recovered by the motor. At the speed of 2000 r/min, 3000 r/min and 4000 r/min, the required minimum steam pressure is around 2.0 MPa, and it also depends on the steam mass flow rate. Combining Figs. 10 and 11, it is not difficult to draw conclusions that bottom cycle output power can meet the requirement of compressor power in the whole speed range. Also, higher steam pressure and lower steam flow rate

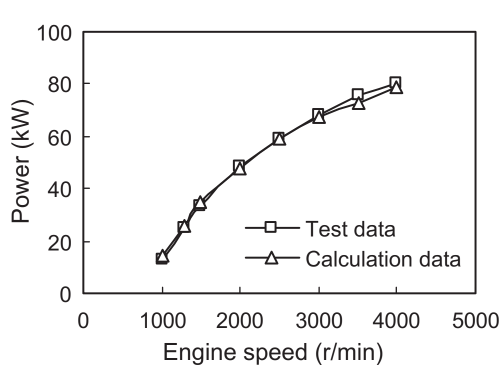

Fig. 8. Simulation results vs. test data (power).

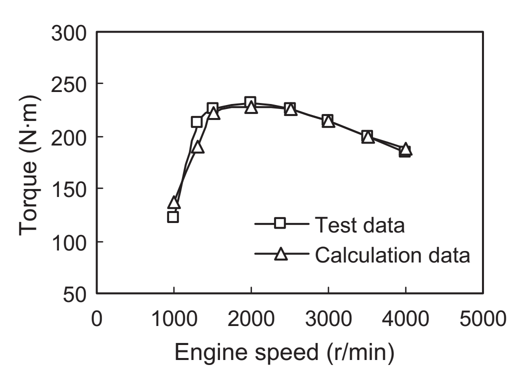

Fig. 9. Simulation results vs. test data (torque).

Table 2
Boundary conditions of the steam turbocharging bottom cycle.

Item	Content			
Engine speed (r/min)	1000	2000	3000	4000
Engine power (kW)	14.9	50.2	70.8	84.8
Exhaust temperature (K)	801.5	862.4	890.8	900.5
Exhaust mass flow rate (g/s)	18.7	59.6	83.3	108.0
Steam turbine efficiency	0.75			
Pump efficiency	0.85			
Turbine outlet steam pressure (bar)	1			
Initial water temperature (K)	298.15			

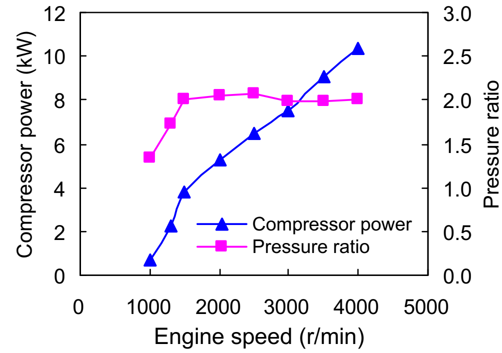

Fig. 11. The required compressor power and pressure ratio under full load.

result in more extra output power. Meanwhile, Fig. 10 gives the reference to select the steam pressure and mass flow rate for steam turbocharging bottom cycle.

6.2. Comparison of IC engine power performances

Then, the effects of steam turbocharging and exhaust turbocharging on IC engine power performances are compared. As mentioned previously, one of the biggest differences between the two kinds of boosting pressure methods is the exhaust pressure. Fig. 12 shows the exhaust pressure of exhaust turbocharging engine and steam turbocharging engine. As can be seen from the figure, when the IC engine is equipped with exhaust turbocharging system, exhaust pressure is higher than 2 bar except at the speed of 1000 r/min, and the maximum exhaust pressure comes up to 2.5 bar at 4000 r/min. However, when the IC engine is equipped with steam turbocharging system, things are changed. Because the pressure resistance in heat exchanger is much lower than the pressure resistance in exhaust turbine, exhaust pressure of steam turbocharging engine is reduced greatly. And the highest exhaust pressure is only 1.4 bar, which also appears at 4000 r/min. The differences of exhaust pressure determine the differences of IC engine pumping losses between the two kinds of boosting pressure methods, as shown in Fig. 13 below. Fig. 13 gives the comparison results of IC engine pumping losses. When the IC engine is equipped with exhaust turbocharging system, the pumping losses are negative except at the speed of 1000 r/min. That is, IC engine exhaust process work is greater than intake process work at all the speeds except 1000 r/min. Especially, when the speed is higher than 2000 r/min, higher speed results in larger pumping loss. Nevertheless, with the steam turbocharging system applied, IC engine pumping loss changes from negative to positive. This is because the exhaust process work is reduced significantly since the exhaust turbine is removed from the exhaust pipe, and it leads to

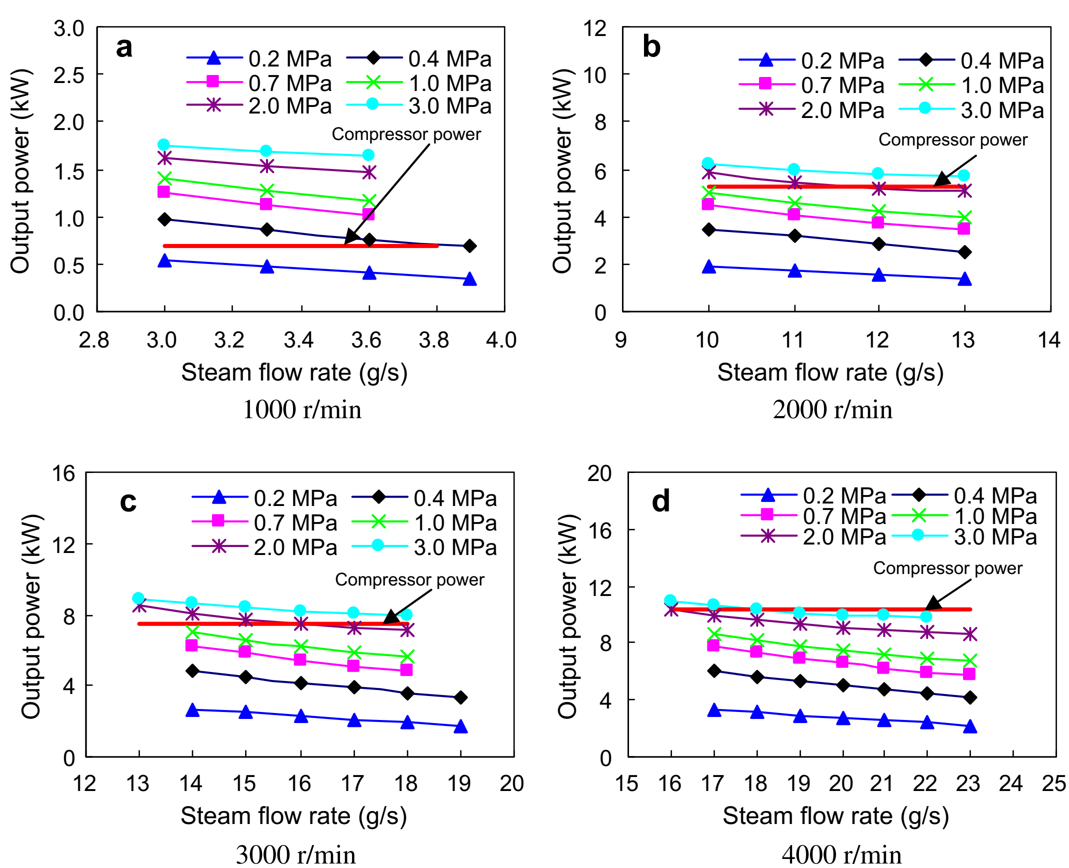

Fig. 10. Output power of steam turbocharging bottom cycle.

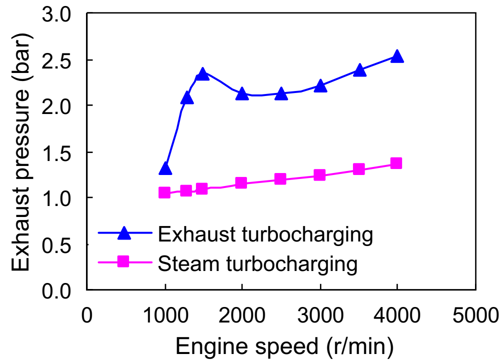

Fig. 12. Comparison of IC engine exhaust pressure.

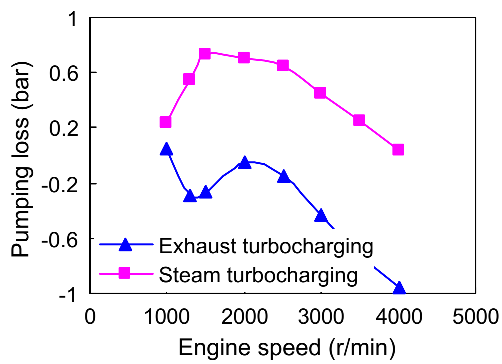

Fig. 13. Comparison of IC engine pumping losses.

the result that intake process work is larger than exhaust process work. According to the above analysis, exhaust turbocharging system inevitably brings in additional exhaust pressure, which requires additional exhaust process work. And now comes the question, what is the relationship between additional exhaust process work and turbine output work? Fig. 14 shows the comparison results of the two kinds of work. As can be observed from this figure, at low-speed, additional exhaust process work is very close to the turbine output work. At medium-speed and high-speed, additional exhaust process work is almost half of turbine output work. Actually, turbine output work results from two parts: one is additional exhaust process work and the other is exhaust expansion work. Among these, additional exhaust process work nearly takes up half of turbine output work at most of speeds. For this reason, exhaust turbine output work is at the cost of increasing additional exhaust process work.

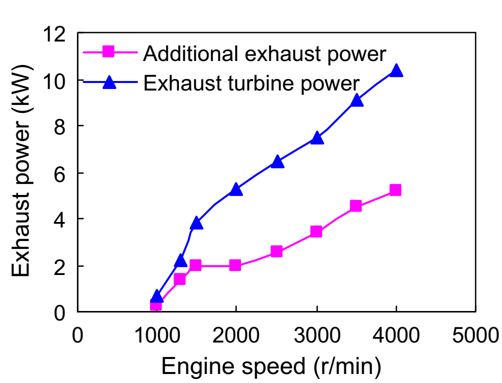

Fig. 14. Comparison of additional exhaust power and turbine output power.

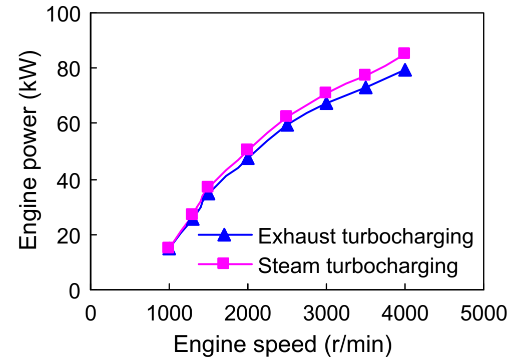

Fig. 15. Comparison of IC engine effective power.

Furthermore, the differences of pumping loss lead to the differences of IC engine effective power. With the steam turbocharging system applied, IC engine effective power can be improved obviously, as shown in Fig. 15. The higher the speed is, the greater the improvement of effective power will be. At the speed of 4000 r/min, IC engine effective power is improved by 5.7 kW. Compared to the exhaust turbocharging engine, the effective power of steam turbocharging engine can be improved by 7.2%. Therefore, steam turbocharging can significantly improve IC engine effective power and dynamic performance. By the way, in Fig. 15, the effective power of steam turbocharging engine dose not include the extra output power of steam turbocharging system since the extra output power not only depends on the IC engine speed, but also the bottom cycle parameters.

6.3. *Comparison of IC engine fuel economy*

Next, the effects of steam turbocharging and exhaust turbocharging on IC engine fuel economy are compared. Fig. 16 shows the comparison results of IC engine thermal efficiency with two kinds of boosting pressure methods under full load. As can be seen from the figure, in the whole speed range, effective thermal efficiencies of steam turbocharging engine are higher than those of exhaust turbocharging engine. With the steam turbocharging system applied, IC engine thermal efficiencies can be improved by 2 percent points or more on the basis of exhaust turbocharging engine except at 1000 r/min. The maximum improvement of IC engine thermal efficiency comes up to 2.7 percent points, which appears at the speed of 4000 r/min. Fig. 17 gives the comparison results of IC engine BSFC. As shown in the figure, when the IC engine is equipped with steam turbocharging system, IC engine BSFC is reduced significantly in the whole speed range, and the

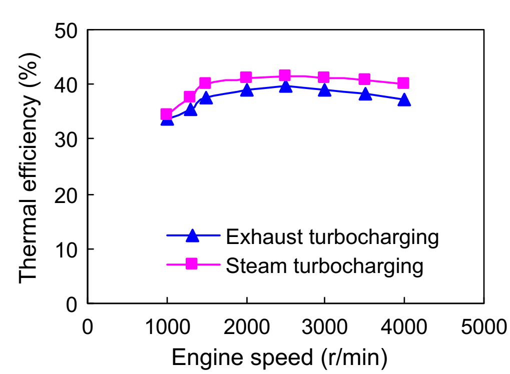

Fig. 16. Comparison of IC engine thermal efficiency.

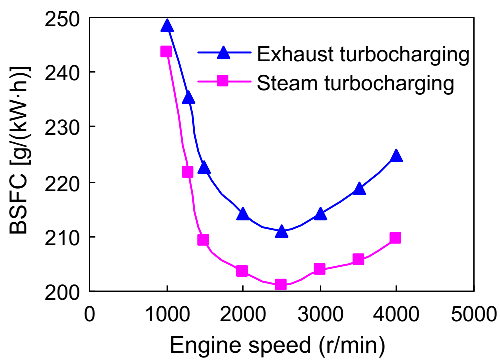

Fig. 17. Comparison of IC engine BSFC.

maximum decrement reaches 15.1 g/(kW h) at the speed of 4000 r/min. This is because IC engine thermal efficiency increases since the exhaust process work is reduced. Through the above analysis, there comes a conclusion that steam turbocharging can effectively improve the energy utilization efficiency of IC engine. As a result, IC engine can have a better fuel economy performance when steam turbocharging system takes the place of exhaust turbocharging system, especially at the higher speed.

7. Conclusions

In this paper, a novel concept of steam turbocharging was proposed to boost IC engine intake pressure. Compared to other boosting pressure means, e.g. exhaust turbocharging, it has lots of advantages and can effectively improve IC engine performances. Based on the analysis above, some conclusions are drawn.

(1) Because exhaust turbocharging system reuses IC engine exhaust energy through exhaust direct expansion, its performances are only determined by exhaust parameters, especially the exhaust pressure. However, steam turbocharging system recovers IC engine exhaust energy based on heat transfer and steam power cycle. And its performances can be optimized by selecting bottom cycle system parameters, such as steam pressure and flow rate. Moreover, this technology can be directly applied on IC engine without changing its main structure.
(2) When the steam turbocharging system is applied on IC engine, both the power and thermal efficiency of IC engine are enhanced on the basis of exhaust turbocharging engine. At the speed of 4000 r/min, the power of steam turbocharging engine can be improved by 7.2%, and the thermal efficiency is increased from 37.3% to 39.9%. All those demonstrate that this steam turbocharging concept has good energy saving potential and application prospects on IC engine.
(3) In the exhaust turbocharging system, turbine output work is at the cost of increasing IC engine exhaust process work. At medium-speed and high-speed, almost half of turbine output work comes from the piston promotion work and the remaining is from exhaust expansion work. At low-speed, almost all turbine output work comes from piston promotion work since the exhaust energy is very low. Consequently, exhaust turbocharging system has direct influence on IC engine working processes. In the steam turbocharging system, all the turbine output work comes from exhaust thermal energy. Steam turbocharging system uses exhaust thermal energy to generate steam for turbine through heat transfer. By this means, it has very little effect on IC engine working processes.
(4) By coupling a motor on the transmission shaft, steam turbocharging system has better performance in the whole speed range. In this way, the motor can effectively manage bottom cycle energy flow, and part of extra output power can be recovered by motor. As a result, IC engine fuel efficiency can be further improved. Usually, higher steam pressure and lower steam flow rate correspond to more extra bottom cycle output power.

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Nomenclature

p	pressure [bar]
η	efficiency [%]
h	specific enthalpy [kJ/kg]
P	power [kW]
$\dot{m}$	mass flow rate [kg/s]
$\dot{\Phi}$	heat flux [kJ/s]
c_P	specific heat [kJ/(kg K)]
T	temperature [K]
γ	specific heat ratio
V_s	cylinder displacement [L]
p_{me}	brake mean effective pressure [MPa]
n	IC engine speed [r/min]
i	cylinder number
τ	stroke number
B	fuel consumption rate [kg/h]
H_u	fuel low heat value [kJ/kg]
b_e	BSFC [g/(kW h)]

Subscripts

pum	pump
st	steam
tur	turbine
bot	bottom cycle
ex	exhaust gas
out	output
mot	motor
com	compressor
in	intake
e	effective power
t	thermal efficiency

Abbreviation

EER	exhaust energy recovery
EAT	electricity aided turbo
IMEP	indicated mean effective pressure
BMEP	brake mean effective pressure
PMEP	pumping mean effective pressure
FMEP	friction mean effective pressure
BSFC	brake specific fuel consumption
VGT	variable geometry turbocharger

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